Coupled Dynamics of the Wave-Atmospheric Boundary Layer at Strong Winds

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Award Number: N00014-08-1-0609

LONG-TERM GOALS

The main goal of the proposed research is to study theoretically the role of the breaking wind waves and the sea spray, generated by them, under strongly forced situations in the airflow dynamics in particular in energy, momentum, heat and moisture transfers through the sea surface. Through this to increase the knowledge of the air-sea interaction and to apply this knowledge for developing improved, physics-based parameterizations of the fluxes (momentum, energy, heat and moisture) in the wave-coupled atmospheric boundary layer. The proposed study is essential to quantify the wave breaking effects on surface transfers, especially in the case of strong winds, where the sea spray generated by breaking waves is believed to play the dominant role in the airflow dynamics. The improved surface forcing (parameterizations of fluxes) is aimed at improvement of the performance of the high-resolution wave and coupled atmosphere-ocean models. The principle innovation of this study is that the airflow and wind waves are considered as a self-consistent interacting coupled system, where the properties of the sea surface (shape of the wave spectrum, wave breaking statistics, etc.) and turbulent characteristics of the atmospheric wave boundary layer are interrelated with each other.

OBJECTIVES

The effect is devided into 4 Tasks.

Task 1. Effect of wind waves and swell on the surface fluxes in the range of wind speeds from calm to very strong when the airflow separation from breaking wave crests dominates the aerodynamic surface roughness.

Objectives Task 1. Development of a generalized model relating the aerodynamic roughness and the surface fluxes to the statistical properties of the sea surface, which can be uniformly adopted in the Marine Atmospheric Boundary Layer (MABL) model for any sea state (developed and developing waves, swell and mixed seas) and wind (from calm to hurricane) conditions.

To study the effect of the airflow separation from breaking waves on the form drag of the sea surface (aerodynamic roughness) at high wind conditions.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2008	**Annual**	**00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE
Coupled Dynamics Of The Wave-Atmospheric Boundary Layer at Strong Winds

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Royal Netherlands Meteorological Institute (KNMI),PO Box 201, 3730 AE De Bilt,The Netherlands, ,

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
The main goal of the proposed research is to study theoretically the role of the breaking wind waves and the sea spray, generated by them, under strongly forced situations in the airflow dynamics in particular in energy, momentum, heat and moisture transfers through the sea surface. Through this to increase the knowledge of the air-sea interaction and to apply this knowledge for developing improved, physics-based parameterizations of the fluxes (momentum, energy, heat and moisture) in the wavecoupled atmospheric boundary layer. The proposed study is essential to quantify the wave breaking effects on surface transfers, especially in the case of strong winds, where the sea spray generated by breaking waves is believed to play the dominant role in the airflow dynamics. The improved surface forcing (parameterizations of fluxes) is aimed at improvement of the performance of the highresolution wave and coupled atmosphere-ocean models. The principle innovation of this study is that the airflow and wind waves are considered as a self-consistent interacting coupled system, where the properties of the sea surface (shape of the wave spectrum, wave breaking statistics, etc.) and turbulent characteristics of the atmospheric wave boundary layer are interrelated with each other.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**6**	

To study the impact of the airflow separation on the near surface turbulence and turbulent momentum and heat fluxes and implementation of results into the existing Wind-Over-Waves Coupling (WOWC) model.

To combine the existing drag-swell (SWELL) and extended WOWC models in one unified model tool describing the sea surface and the near surface turbulent fluxes in a wide range of sea state and wind conditions.

Task 2. Development of a model of the spume droplets production.

Objectives Task 2. Development of a theoretical model of the spume droplets generation, which relates the rate of the spume droplets production and distribution of droplets over size to the wave breaking statistics, sea state conditions and the wind speed. To compare the model results with existing and new High-Resolution Wave-Air-Sea Interaction DRI experimental data.

Task 3. Investigation of the impact of sea droplets on the structure of the MABL and the exchange processes at the sea surface at strong wind conditions.

Objectives Task 3. Development of a MABL model coupled with waves that is valid in a wide range of the wind speed conditions, up to the wind of a hurricane force.

To investigate the effect of sea droplets on the atmospheric turbulence, turbulent fluxes, wind and temperature profiles through their impact on the buoyancy force and the spray stress.

To investigate how the sea spume droplets and the airflow separation are tied together in setting of momentum, heat and moisture fluxes at the sea surface.

Establishing new parameterizations of the sea surface transfer coefficients, and the parameters of the lower atmosphere like sea droplets concentration aiming at use and improvement of the wave/atmospheric/upper-ocean modeling including hazardous wind conditions.

Task 4. Testing of the model development on the dedicated DRI experiments and application of the model approach for the experimental data analysis.

Objectives Task 4. Application of the WOWC, SWELL, MABL, newly developed WOWC-SWELL and MABL-WOWC models for the interpretation of the High-Resolution Wave-Air-Sea Interaction DRI experiments.

APPROACH

The study is based on the Wind-Over-Waves Coupling theory/model developed by the offerors in the last decade. WOWC is a modern theory/model of microscale air-sea interaction, which allows relating the sea drag (surface stress) directly to the properties of wind waves and peculiarities of their interaction with the wind (Makin, 1998, 2005; Makin et al. 1995; Makin and Kudryavtsev, 1999, 2002, 2003; Kudryavtsev et al., 1999; Kudryavtsev and Makin, 2001, 2002). The WOWC model is based on the conservation equation for integral momentum, which relates the friction velocity to the surface

stress supported by viscous stress and the form drag. The form drag is supported by the wave-induced stress and by stress due to separation of the airflow from breaking wind waves. The theory provides a clear understanding of the physical mechanisms forming the surface stress, and an explanation on what causes the stress dependence on the wind speed, wave age, finite bottom depth, and other ocean and atmosphere parameters. Thus the research combines a theoretical/modeling approach to describe the air-sea interaction in the full range of wind speeds including extreme winds with the use of existing and new field and laboratory data for a model validation and interpretation of the experiments. It will utilize the knowledge to be obtained in parameterizations of the sea surface exchange processes, the sea drag coefficient in the first place.

The experimental effort, which underpins the present DRI, and the theoretical analysis of its results, which is offered by the present research effort, are deeply interrelated. On one side, the experiment will provide new data to check theoretical assumptions of the model. On the other, the WOWC model directly relating the surface exchanges, momentum flux in the first place, to the properties of the sea surface and its interaction with the airflow allows a clear physical explanation how the sea surface stress is formed and regulated by the surface phenomena. Waves play in that processes the dominant role. The WOWC model was successfully applied to predict stresses in a wide variety of low to moderate wind speeds and sea-state conditions. At strong wind speeds actively breaking waves and corresponding sea spray and foam production could significantly change the exchange processes.

Focusing on investigation of the air-sea interaction at high winds the WOWC model will be extended to account for the impact of the separation on the aerodynamic roughness of the sea surface by the intensive sheltering of the sea surface by separation bubbles, and the impact of the spume droplets, generated by intensively breaking waves, on the structure of the MABL including surface exchanges.

An experiment, although is an ultimate truth, is hardly able to separate effects of the multiple influences involved in the coupled system ocean-waves-atmosphere. This can be done within the theoretical/numerical models, by switching on and off different physical mechanisms. If, for particular conditions, the experiment and the model produce identical or close results, we assume that physics included in the model is adequate for the relevant field circumstances. If, on the contrary, there are essential discrepancies between the measurement and the model, such cases will be scrutinised to find the cause.

PI Dr. Vladimir Makin (KNMI) and Co-PI Prof. Vladimir Kudryavtsev (RSHMU) are the key individuals participating in this work. They coordinate the effect, develop theoretical ideas of the research, and participate in models construction and modeling. They participate in the analysis of model results and comparison studies with experimental data.

WORK COMPLETED

Task 1 to study the effect of wind waves and swell on the surface fluxes in the range of wind speeds from calm to very strong when the airflow separation from breaking wave crests dominates the aerodynamic surface roughness with the objective to study the effect of the airflow separation from breaking waves on the form drag of the sea surface (aerodynamic roughness) at high wind conditions is completed.

RESULTS

The role of the surface roughness in the formation of the aerodynamic friction of the water surface at high wind speeds is investigated. The study is based on the WOWC theory. In this theory waves provide the surface friction velocity through the form drag, while the energy input from the wind to waves depends on the friction velocity and the wind speed. The WOWC model is extended to high wind speeds taking into account the effect of sheltering of the short wind waves by the air flow separation from breaking crests of longer waves. It is suggested that the momentum and energy flux from the wind to short waves locally vanishes if they are trapped into the separation bubble of breaking longer waves. It is shown, that at short fetches, typical for laboratory conditions and strong winds, the steep dominant wind waves break frequently and provide the major part of the total form drag through the airflow separation from breaking crests, and the effect of short waves on the sea drag is suppressed. In this case the dependence of the drag coefficient on the wind speed is much weaker than would be expected from the standard parameterization of the roughness parameter through the Charnock relation. At long fetches, typical for the field, waves in the spectral peak break rarely and their contribution to the airflow separation is weak. In this case the surface form drag is determined predominantly by the air flow separation from breaking of the equilibrium range waves. As found at high wind speeds up to 60 m/s the modeled aerodynamic roughness is consistent with the Charnock relation, i.e. there is no saturation of the sea drag. Unlike the aerodynamic roughness, the geometrical surface roughness (height of short waves) could be saturated or even suppressed when the wind speed exceeds 30 m/s. The study suggests that other effects like impact of the sea spray generation should play a significant role in the air-sea interaction in the open ocean.

A simple model of the atmospheric boundary layer over the ocean where the swell impact on the atmosphere is explicitly accounted for is suggested. The model is based on Ekman's equations, where the stress in the wave boundary layer is split into two parts: the turbulent and wave-induced stress. The turbulent stress is parameterized traditionally via the eddy-viscosity proportional to the generalized mixing length. The wave-induced stress directed upward (from swell to the atmosphere) is parameterized using the formalism of the wind-over-waves coupling theory. The model could be seen as an extension of the model by Kudryavtsev and Makin (2004) to the scale of the entire atmospheric boundary layer by including the Coriolis force into the momentum conservation equation and generalizing the definition of the mixing length. Extreme regime of low winds for swell propagating along the wind direction is studied. It is shown that the impact of swell on the atmosphere is governed mainly by the swell parameter - the coupling parameter that is the product of the swell steepness and the growth rate parameter. When the coupling parameter drops below -1 the impact of swell becomes significant and alters the entire atmospheric boundary layer. The turbulent stress is enhanced near the surface as compared to no-swell case. It becomes negative above the height of the inner region of swell. The wind profile is characterized by a positive gradient near the surface and a negative gradient above the height of the inner region forming a characteristic bump at the height of the inner region. Results of the model agree at least qualitatively with observations performed in the atmosphere in presence of swell.

IMPACT/APPLICATIONS

The main innovation of the project is the development of the advanced model describing the exchange processes at the sea surface in extreme wind conditions. This covers the improved description of the sea surface and the WOWC model, and assessment of the sea spray role in the momentum flux above the sea. The project will provide new knowledge and parameterizations of the sea surface fluxes,

which will be valid for the whole range of wind speeds and sea surface conditions and can be used as improved boundary conditions for high-resolution numerical models of ocean, atmosphere, and coupled ocean-atmosphere systems, and covers all spatial and temporal scales from local high-resolution to global climate studies. Therefore, this study directly addresses social needs to improve climate variation predictions, weather forecasts and to reduce the impact of natural hazards caused by extreme wind and sea-state conditions.

RELATED PROJECTS

PhD research "Air-sea interaction and sea-state forecasts in extreme weather conditions", 2007-2011, funded by Netherlands Organization for Scientific Research. The main goal of this research is to apply consistently new parameterizations of the sea drag to the sea state and atmosphere models with focusing at extreme weather conditions and aiming at models improved performance. Parameterizations, which will be obtained in the course of the DRI effort, are obvious candidates for the testing. A PhD student will participate also in theoretical development of the models identified in DRI effort.

REFERENCES

1. Kudryavtsev, V.N. and Makin, V.K.: 2001, 'The impact of the air flow separation on the drag of the sea surface', *Boundary-Layer Meteorol*., **98**, 155-171.
2. Kudryavtsev, V.N. and Makin, V.K.: 2002, 'Coupled dynamics of short wind waves and the air flow over long surface waves', *J. Geophys. Res*., **107**, C12, 3209, doi:10.1029/2001JC001251.
3. Kudryavtsev, V.N. and Makin, V.K.: 2004, 'Impact of swell on marine atmospheric boundary layer', *J. Phys. Oceanogr,* **34**, 934-949.
4. Kudryavtsev V.N., Makin, V.K. and Chapron, B.: 1999, 'Coupled sea surface-atmosphere model. Part 2. Spectrum of short wind waves', *J. Geophys. Res*., **104**, C4, 7625-7639.
5. Makin, V.K.: 1998, 'The air-sea exchange of heat in presence of waves and spray', *J. Geophys. Res*., **103**, 1137-1152.
6. Makin, V.K.: 2005, 'A note on drag of the sea surface at hurricane winds', *Boundary-Layer Meteor*., **115**, 169-176.
7. Makin, V.K. and Kudryavtsev, V.N.: 1999, 'Coupled sea surface-atmosphere model. Part 1. Wind over waves coupling', *J. Geophys. Res*., **104,** C4, 7613-7623.
8. Makin, V.K. and Kudryavtsev, V.N.: 1999, 'Dynamical coupling of surface waves with the atmosphere', p. 73-126, in: *Air-Sea Exchange: Physics, Chemistry and Dynamics,* ed. G. L. Geernaert, Kluwer Acad. Publ., 579 p.
9. Makin, V.K. and Kudryavtsev, V.N.: 2002, 'Impact of dominant waves on sea drag', *Boundary-Layer Meteorol.,* **103**, 83-99.
10. Makin, V.K. and Kudryavtsev, V.N.: 2003, 'Wind-over-waves coupling', pp. 46-56, in *Wind Over Waves* II, ed. Sajjadi, S.G. and Hunt, J.C.R., Horwood Publishing Limited, England, 232 p.
11. Makin, V.K., Kudryavtsev, V.N. and Mastenbroek, C.: 1995, 'Drag of the sea surface', *Boundary-Layer Meteorol.,* **73**, 159-182.

PUBLICATIONS

1. Kudryavtsev, V.N. and Makin, V.K.: 2007,'Aerodynamic roughness of the sea surface at high winds', DOI 10.1007/s10546-007-9184-7, *Boundary-Layer Meteor.*, **125**(2), 289-303 [published, refereed].
2. Kudryavtsev, V.N. and Makin, V.K.: 2007,'Aerodynamic roughness of the sea surface at high winds',

in *Atmospheric Boundary Layers*,133-148, eds. A. Baklanov, B. Grisogono, Springer [published, refereed].

3. Makin, V.K.: 2008, ‘On the possible impact of a following-swell on the atmospheric boundary layer’, *submitted to Boundary-Layer Meteor*.